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Cost Performance and Risk in the Construction of Offshore and Onshore Wind Farms

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Abstract: This article investigates the risk of construction cost overruns or underruns occurring in the construction of 51 onshore and offshore wind farms commissioned between 2000 and 2015 in thirteen countries. In total, these projects required about $39 billion in investment and reached about 11 GW of installed capacity. We use this original dataset to test six hypotheses about construction cost overruns related to (1) technological learning (2) fiscal control (3) economies of scale, (4) configuration (5) regulation and markets and (6) manufacturing experience. We find that across the entire dataset, the mean cost escalation per project is 6.5% or about $63 million per windfarm, although 20 projects within the sample (39%) did not exhibit cost overruns. The majority of onshore wind farms exhibit cost underruns while for offshore wind farms the results have a larger spread. Interestingly, no significant relationship exists between the size (in total MW or per individual turbine capacity) of a windfarm and the severity of a cost overrun. Nonetheless, there is an indication that the risk increases for larger wind farms at greater distances offshore using new types of turbine and foundations. Overall, the mean cost escalation for onshore projects is 1.7% and 9.6% for offshore wind farms that still ranks much lower than for other significant infrastructure.

Keywords: wind energy; wind power; construction cost overrun; energy and finance

1. Introduction

Wind energy is one of the fastest growing, and cleanest, sources of electricity on the global market today and an important industry worldwide. During the past decade, global cumulative wind energy deployment increased by a factor of seven, from 48 GW installed in 2004 to more than 370 GW installed by the end of 2014. More than 90 countries installed commercial wind farms in 2012.[1] In many regions, including Denmark, new wind installations actually generate electricity more cheaply than conventional fossil fueled or nuclear plants.[2] Even in the United States, where 67% of electricity generated in 2014 was from fossil fuels[3], researchers at Lawrence Berkeley National Laboratory surveyed the actual production costs from 128 separate wind farms and found they tended to produce electricity for less than 5 cents per kWh, making them cheaper than wholesale prices for electricity.[4] Furthermore, power providers can often build wind farms more quickly than larger-capacity conventional generating plants. This can enable them to meet incremental demand growth with less economic risk, and the employment of wind energy systems diversifies the fuel mix of utility companies, thereby reducing the danger of fuel shortages, fuel cost hikes, and power interruptions, whilst meeting demand for reduced greenhouse gas emissions.[5]

Like all large infrastructure projects, wind farm development contains risk. Developers aiming to capture larger wind resources both on- and offshore have faced risks of cost and time overruns related to construction and erection of turbines. Vestas temporarily withdrew completely from the offshore wind sector following difficulties with gearboxes at Horns Rev, Scroby Sands, Kentish Flats, and Barrow.[6] In their first offshore venture at Horns Rev I, they had to retrofit generators and transformers at all 80 turbines of the park at a cost of €417 million.[7] Anticipating similar problems with one of their own projects, Siemens Wind Power withdrew from discussions over an engineering, procurement, and construction contract worth €460 million at Lynn and Inner Dowsing (two proposed separate 108 MW sites) in the United Kingdom.[8]

In the present article, we assess the extent and severity of cost performance (overruns or underruns) occurring in the construction of 51 onshore and offshore wind farms commissioned between 2000 and 2015 in thirteen countries. In total, these projects demanded about $39 billion in investment and reached about 11 GW of installed capacity. We depend on this dataset, which was generated from internet and academic databases searches using keywords, and statistical analysis of its content, to examine six hypotheses shown in Table 1.

2. Concepts and Methods

The most basic concept underlying our study is that of "construction cost," the price of assembling and transporting components, carrying out civil works, and installing components and equipment before commercial operations commence, a term also sometimes referred to as the cost of "Engineering, Procurement, and Construction" or "Engineering, Procurement, Installation and Construction."[9] [10] More specifically, for onshore turbines, when initial developing, designing, public approval and planning has been carried out the main construction works encompasses the following eight stages[11]:

- Clearing of terrain;
- Building of access roads;
- Earthworks;
- Concrete foundation works;
- Transport of turbine elements;
- Assembly of turbines;

- Electrical installation; and
- Testing and commissioning.

The construction of offshore wind farms is a bit different, given that construction works have become increasingly advanced and capital intensive due to the use of specialized equipment and vessels.[12] [13] The development processes include preparing (building) harbor and other facilities onshore to prepare the transportation of foundations and turbine elements to the site. Construction works involves preparing the seabed, grounding foundations, producing, transporting and erecting foundations (typically monopiles or gravitation). Contractors then usually erect the substation and cabling for connecting the wind farm to the electrical grid. The assembly of offshore turbines is therefore typically longer than for onshore turbines.[14] [15]

Because scant information about onshore and offshore wind energy cost performance existed in the peer-reviewed literature, we proceeded to compile an original dataset. We did so by searching for the words “wind energy,” “windfarm,” “wind farm,” “wind power,” and “wind turbine” in the same sentence as the words “construction,” “cost,” “overrun,” “building,” and “escalation” on a series of academic databases (including ScienceDirect and EBSCO host) as well as the internet (using Google and Safari). Some of the data were also located in two prominent websites: http://www.thewindpower.net/ and www.lorc.dk/offshore-wind-farms-map/lis.

We included a project in our dataset only when we could find complete data regarding the year of project commissioning, its location, its formal name, its capacity in MW, its configuration as onshore or offshore, and its quoted/estimated construction cost as well as its real or eventual construction cost. We then updated all costs and currencies to US$2012, with the final data presented in Appendix I for all 51 projects, using Oanda’s historical currency converted (adjusting for purchasing power parity) and then the Statistical Abstracts of the United States to convert historical dollars to current dollars. Our dataset includes 20 manufacturers including General Electric, Goldwind, Siemens Wind Power, Suzlon, and Vestas as well as 38 developers including DONG Energy, E.On, Scottish Power, and Vattenfall. The Spearman coefficient of determination has been used to test the relationship strength between different variables within our data because the Spearman's rank correlation is suited to both continuous and discrete variables.

Naturally, a few caveats deserve mentioning. In some sense, each wind project is unique, given that it will involve a distinct combination of permutations relating to developer, subcontractors, turbine type, location, owner and operator and so on. So, while we hold that our assessment is useful at depicting industry trends, it holds less validity for thinking about the implications of specific individual projects in characteristic contexts. Also, rather than attempt to evaluate the veracity or completeness of our individual cost estimates, which numbered close to 200, we took their assessments at face value. In some cases, where no direct cost overrun was reported, we interpreted it ourselves by comparing the initial quoted cost and the final delivered cost. Moreover, we searched primarily in Danish, English, and German, secondly in Swedish and French, and we wanted verification of performance, meaning unpublished or non-reported accounts, accounts in periodicals not searched, and publications in other languages were excluded. This created a bias towards European and North American projects within the dataset.

3. Results and Discussion

Figure 1 presents a frequency distribution for the dataset (given in the Appendix). As indicated, 20 of 51 wind farms (39%) did not exhibit cost overruns. Most wind farms (37, or 73% of the sample) had a minor cost underrun (10 % or less), were on budget, or had a minor overrun (less than 10%) and only 13 had an overrun of greater than 10%. Of these 13, 10 were offshore and this is where the largest overruns occurred. Across the sample the mean overrun was 6.5%

cost escalation or about $63 million per windfarm. It is worth noting here that our sample of offshore wind farms contains 7.6 GW compared to approximately 12 GW installed offshore wind energy capacity (63%) worldwide at the end of 2015. However our onshore sample is relatively small (around 4 GW of about 410 GW installed onshore wind energy capacity at the end of 2015). The remainder of this section discusses the results of testing our dataset with the six hypotheses shown in Table 1.

H1: Innovation and learning

The first hypothesis is that as manufacturers and developers gain more experience with building windfarms, the risk of overruns will decline. This trend is sometimes termed "technological learning," and it can relate both to the "hard" manufacturing of wind turbine components as well as "soft" costs such as resource assessments, permitting and siting, and installation [16]. For example, it has been estimated that achieving 20 % market share for wind energy would bring large-scale development and nationwide standards that would, in turn, lower costs.[17] This "learning by doing" approach has been projected by many other studies to lower the expense of producing, installing, and maintaining wind turbines.[18] [19][20] Sawin found that every doubling of manufacturing volume for wind technologies corresponded with an 8 to 10 % reduction in cost.[21] Also, previous qualitative studies of learning in the Danish wind sector have indicated the presence of a learning effect, not only in a "learning by doing" fashion, but also in a more R&D-based manner. [22] [23] There is further evidence that learning applies to onshore and offshore wind turbine construction techniques. Validating this trend, Levitt et al. noted that costs for a "first of a kind" wind project tended to be almost twice as much as the "best recent values" for offshore wind farms, implying that learning can quickly lower construction cost.[24]

The dataset supports this hypothesis for onshore turbines but not offshore turbines. As shown in Figure 2, cost overruns have a negative relationship with year for onshore wind farms, but not for offshore wind farms in the dataset. One possible explanation for fewer overrun risks for onshore wind farms is that the specific sector is more mature, and better able to control defects. For instance, product defects have been a recurrent source of overruns in the erection of wind farms, as defects stemming from particular components or suppliers can become unknowingly inherited. Such defects, like in the control system, tend to surface during testing, late in installation phase. Some wind turbine manufacturers outsource parts of their production and procure components and therefore the quality of the finalized turbine is dependent on the successful quality control in production and successful governance of the supply chain[25]. This diffusion of responsibility to suppliers occurs under competitive conditions as many western manufacturers are in a race of cost reduction to keep up with newly emerging Chinese players, and to compete in new markets with less attractive wind conditions demanding a lower cost per produced MWh. It does appear that leading onshore manufacturers have been able to mitigate quality problems better over the last ten years, which may explain few overruns in the later years.

Why is there not more learning occurring for offshore wind farms? One obvious explanation would be the greater fragmentation of the wind and construction industries. In the wind industry there are numerous companies involved in manufacturing offshore wind turbines and in 2014 the market leader, the Danish company Vestas, had only an 11.6 % market share. As Figure 3 shows, the top ten manufactures as of 2014 still accounted for only 68.5 % of the worldwide fleet of wind turbines and these companies were spread across China, Denmark, Germany, India, Spain, and the United States. Figure 3 introduces the leading wind turbine manufacturers by global market share, including both onshore and offshore installations. However, it is worth mentioning, that when dividing the two configurations, it becomes clear that Siemens Wind Power were the offshore market leader having a share of 86.2% of the dominating European offshore market in 2014, whereas Vestas only had 9.5% of the market share. Other manufacturers are Areva with an offshore market share of 3%, Senvion with 0.8%, and Samsung with 0.5%.[26]

Furthermore, even within these companies, approaches to wind turbine design and construction are usually disjointed. Wind energy manufacturing is engineering intensive and requires integrated competencies—spread across foundations, vessels, cables, blades, towers, and so on. These competencies can cut across at least ten dimensions including mechanical engineering, electrical engineering, physics, software engineering, civil engineering, aeronautics, meteorology, health and safety operation and project management. This means that "learning effects are balanced by an increased demand for engineering inputs" and that gaining "deep and integrated competence … is a daunting task."[27] A similar pattern, fragmented companies and competences, can be found in the part of construction industry that participates in the making of wind farms.

As a final contributing factor stunting the ability to learn, most major manufacturers rely on a variegated and constantly changing array of subcontractors, often small and medium enterprises which sometimes go bankrupt, for many key components. For instance, there was rapid turnover among the firms laying cables for offshore wind farms in Europe in the mid- to late 2000s, with many companies filing for insolvency. The consequence was that when such companies disbanded, their ability to transmit knowledge was limited, and new entrants had to relearn previous lessons, adding to both delays and cost. Although the laying of cables represented only 1 to 7 % of the capital expenditure for a typical offshore wind farm during this period, in many instances cables attributed to up to 80% of problems and delays. Learning was inhibited by the turbulent market dynamics affecting subcontractors. Particularly for offshore, there are new players entering the market, and new larger turbines are being deployed into deeper waters further from land that increases the overall risk (see next sections).

H2: Simplicity and fiscal control

The second hypothesis was that projects with smaller budgets would exhibit a greater potential for savings through underruns. This is based on the intuitive logic that projects demanding fewer resources—i.e., smaller budgets—would have more accurate budgeting forecasts and be more likely to precipitate in cost underruns. Smaller budgeted projects would also, the thinking goes, have relatively simpler contracting arrangements and less need for extensive resource assessments, financing charges, and/or labor relations. Research investigating transport projects has also noted that rail and road projects resulting in underruns tended to have better control over budgets due to factors at the pre-construction phase[28], i.e. related to issues like financing charges or setting up arrangements with subcontractors, rather than during the construction phase. Moreover, smaller budget projects would naturally include fewer wind turbines, which at least for offshore wind farms reduces exposure to potentially disruptive weather conditions and could allow for more efficient installation and transportation of components, other materials, and labor. Indeed, delays in offshore wind projects due to inappropriate weather conditions are considered to be one of the major risks facing the offshore wind industry.[29] The subtle implication here is that preliminary soft costs and budgeting processes can significantly affect final project expenses.

Tellingly, the subsample of 19 projects that had a total $436 million in underruns (combined project savings), there was no significant effect as indicated by the Spearman coefficient of determination r^2 (r^2 =0 .01) between the size of a budget and the extent of an underrun. One explanation could be that smaller project budgets involve smaller subcontracts and firms that are not as professional as the larger, megaprojects. Another could be that budget size is not indicative of fundamental changes in technical design, resource assessments, or labor. A 50 MW wind farm, for instance, will still involve many of the same technical attributes as one ten times as large and smaller projects will not have the same advance of mass-producing parts for the potential site-specific wind turbines. Wind farms, being modular and scalable, means the possibility of an underrun remains roughly the same regardless of the final aggregate electrical capacity of the project.

H3: Economies of Scale

This hypothesis holds that as wind farms get larger—a greater number of turbines, or turbines of a higher capacity in MW—the frequency and severity of cost overruns will rise. The relatively decentralized and distributed nature of wind resources has created pressure to scale up to bigger units to get the most performance out of available sites. Several firms, including Vestas, Siemens Wind Power and Repower, are developing turbines larger than 5 MW, for example at 7 MW and even looking at the opportunities for 12 MW turbines[30]. Indeed, the average capacity (in MW) for an individual offshore wind turbine as part of an aggregated wind farm was below 1 MW in the 1990s, whereas in 2005 it reached 3 MW and the newest planned installations have up to 8 MW capacity turbines.[31] [32] The average windfarm presented in the database has a rated capacity of 220 MW, when including both on- and off-shore wind farms. This number is greater than previous estimates (17.2 MW for the average wind farm installed in the EU[33]) which include many small projects. However, following the trends estimated by Ernst and Young[34] and IRENA[35], stating that the offshore installed capacity will increase more rapidly than its onshore counterpart in the coming years, it can be assumed that the dataset presented in this research presents a realistic image of future wind farms.

This desire to build larger windfarms, though intuitive, does come with increased risk. Especially for the onshore wind farms in Western Europe, where the process of scaling up the installed capacity at windfarms is often performed through the installation of larger wind turbines (MW), due to lack of space, which can be fraught with technical and economic difficulties.[36] Larger projects are more difficult to mass produce although they should also produce efficiencies.[37] [38] The almost site-specific nature of mega-turbines makes them "highly variable" in terms of performance, with one assessment cautioning that "the present approach to up-sizing, as you get towards the 6 MW and 10 MW machines now in prospect, will bring issues of repeatable quality, and that the cost of overcoming these will be prohibitive."[39]

The historical record of two other energy systems—nuclear reactors, and thermoelectric boilers—lends further support to this hypothesis, as both faced problems in scaling up capacities. Grubler noted that the scaling up of nuclear reactors in France succumbed to "negative learning," when the next generation of a product or technology involved higher costs or greater rates of failure than its previous generation.[40] Hirsh also found in the United States that electric utilities ran into "technological stasis" as they attempted to build extremely large power plants.[41] [42]

In part, the dataset bears out the above as shown in Figure 4. For onshore wind farms, cost underrun/overrun is close to zero and there is a slight downward trend in cost overrun with time but no correlation between cost underrun/overrun and size (r^2=0.00). However as offshore wind farm size increases, the variability or spread of values for cost underrun/overrun increases and there is a slight upward trend in overrun with size although r^2=0.02.

Why is there no significant correlation between cost overrun and the size (MW) of the wind project? One obvious explanation would be the fact that many wind turbine components are mass-produced and parts are preassembled, decreasing some of the onsite construction risk. Moreover, the companies building or developing projects with an installed capacity of more than 150 MW—notably Siemens, DONG, Vattenfall, and E.ON—are either vertically integrated complex manufacturing conglomerates, or large integrated utility firms. Such large utility firms are both familiar with managing large portfolios of products and greater experience compared to the companies developing smaller projects. This could mitigate diseconomies of scale because they can capture many of the innovation features usually found within small and medium enterprises.[43] [44] [45]

Figure 5 shows, when disaggregated by configuration and turbine size, offshore wind farms see overrun risks increase as larger 4 and 5 MW turbines are utilized. However, in order to directly compare cost overruns for onshore and offshore projects, more detailed analyses will be carried out in the next section.

H4: Technological configuration

Our fourth hypothesis is that offshore windfarms would see a greater risk of overruns than onshore windfarms. This is because offshore wind involves a higher scale of investment and thus financing, with projects often exceeding $1 billion and involving a greater number of turbines. This means customers are larger integrated utilities such as DONG Energy or Vattenfall rather than the more size differentiated smaller firms and citizens cooperatives who invest in onshore projects. It also means projects become more industrial and susceptible to risks common in megaproject management.[46] [47] [48] Additionally, contrary to expectations, the costs of offshore wind have not followed the cost development pattern of onshore wind, but have in fact increased significantly since the mid-2000s.[49]

Part of the explanation for this is simple: harsher conditions than land-based sites. Areas with strong winds also have heavy waves and require more robust towers and foundations, and in recent years, wind manufacturers have developed wind turbines with larger rotors for offshore sites, in order to maximize the energy harvest from the strong winds. Blades and nacelles are exposed to greater loads and the effects of corrosive salt spray.[50] These conditions lead to unique engineering and maintenance requirements. A typical offshore turbine, for instance, can require more than 100,000 components[51] when onshore models have between 50,000 and 80,000 components. An additional complication is the variable nature of the sea and weather conditions which can impact the availability or efficiency of expensive vessels used for installation of offshore turbines, leading to unexpected delays.

Moreover, offshore windfarms are less standardized than their onshore counterparts. So far, there is no universal platform or foundation, no standard type of support structure suitable for all offshore wind sites. So instead, a heterogeneous mix of support structures have been used in practice, ranging from monopiles, suction buckets, and gravity-based fixed bottom structures for shallow water to jackets and tripods for transitional water and floating platforms for deep water.[52] [53] Under certain conditions, an ice- breaking cone is even needed at the water surface level.[54]

Lastly, offshore wind farms have more complex construction processes and thus contracting requirements. Compared to offshore turbines, the construction works for onshore units are simpler, involve less risks, and less equipment. Central equipment include trucks for transporting material and turbines, a crane for assembly processes, and a concrete pump for pouring in concrete once formwork are finalized. Formwork is mostly carried out at the site. At smaller wind farms it is often local civil engineering companies that extend their activities and competences from other types of civil engineering concrete works into this area. Construction works of this kind occurs quite widespread all over the world.

By contrast, offshore construction processes are highly risky due to the variability of the sea and other weather conditions iterated above. It is usual to employ a range of vessels when installing the wind turbines, and it is, at times, labour intensive. Also the dependency on specialized vessels create risks as the vessels might be employed elsewhere. The contracting structure is complicated and can involve fifty plus separate contracts.[55] For instance, a typical contract holder would be Vestas or Siemens, but these companies subcontract the foundation work to large contractors such as Hochtief, Bilfinger Berger, MTH, and still other important subcontractors would be vessel suppliers such as A2SEA.

Interestingly, our dataset confirms this hypothesis. Onshore wind farms have lower mean (0.8%) and median (-0.5%) cost escalation compared to offshore windfarms with a mean cost escalation of 9.6% and a median escalation of 5.7% (Table 2). Part of the explanation is foundation. The foundation is the heaviest part of a combined wind turbine installation, and foundations for offshore windfarms are larger, stronger, and more materials and capital intensive. Concrete foundations— used in shallow water offshore and needed as turbines get larger in size and capacity, since more stability is required—weigh three times as much the steel foundations. The installation cost of gravity based foundations can vary by 20% simply based on geology and the presence of hard clay, sand, or loose clay.[56]

Table 2 presents the average cost overrun (%) for the three categories of foundation in the offshore wind projects. Monopile foundations are the most installed offshore foundation type worldwide, accounting for almost three-quarters of all offshore foundations at the end of 2012.[57]

[58] Traditional monopile foundations are, however, along with gravity based foundations most applicable for shallower waters, and with the recent trend of manufacturing bigger wind turbines and locating them in deeper waters, the demand for other foundations is increasing—and with it higher costs, technical uncertainties, and lack of experience.[59] Thus, as shown in Figure 6, newer projects in deeper water, built further from shore have shown some tendency to cost overrun but aren't necessarily the projects with the largest overruns. This is likely to be one of the main incentives for the development of new extra-large monopiles suitable for deeper waters.

H5: Regulatory regimes and markets

Our fifth hypothesis was that, overall, location would matter. States, regions, or jurisdictions with stronger governance frameworks demanding improved social and environmental impact assessments, stakeholder involvement, transparency, and accountability would see lower incidences of cost overruns than locations with weaker governance frameworks.[60] A related part of this hypothesis concerned procurement and inflation: generally, countries with weaker governance regimes also see more volatility in their currencies and are prone to delays related to shortages of materials or labor.[61] Also, when it comes to infrastructure and construction projects, so-called developing countries (or least developed, low income, or lower middle income countries to use parlance from the World Bank) tend to lack experience building complex technological projects compared to so-called developed countries (or upper income/upper middle income countries).[62]

The data are relatively limited given the smaller sample sizes of each of the subclasses, as Table 3 indicates we were unable to support this hypothesis. Although, the lowest mean and median cost overruns occur in North America and Australia—both highly developed countries—overruns in Europe, known for more stringent regulations than both Australia and the United

States, are almost on par with those in Asia, where inconsistency between the development of wind projects and grid planning has led to costly regulatory delays.[63]

This finding relates to the configuration and type of technology being deployed, since all but one of the offshore wind farms is located in Europe and is suggested by the breakdown of European wind farms into onshore and offshore shown in Table 3.

H6: Manufacturing experience

Our final hypothesis was that manufacturers with greater historical experience would have less frequent and less severe overruns. (Although manufacturers supply turbines but developers take responsibility for a project, the manufacturer must meet construction timetables and budgets). To test this hypothesis, we categorized two classes of manufacturers, those with 5 or more projects in the sample—in fact only three manufacturers, General Electric, Siemens Wind Power, and Vestas—and those with four projects or less. More specifically, this latter group involved twelve other firms: Areva Wind, BARD, Bonus Energy, Enercon, Goldwind, Guodain, NedWind, Nordex, Repower, Senvion, Suzlon, WinWind. We excluded three projects from this categorized sample that did not fit into either group, being jointly implemented by hybrid consortia, one of Alstom and Siemens and two between Suzlon and Senvion

Our results, shown in Table 4, indicate that the class of manufacturers with a project experience of 5 or greater experience slightly fewer overruns. When looking at cost escalation as a mean average, the amount does not have much variance—a mere 0.4% between the two classes. The median, however, shows a greater divergence, 1.08% compared to 4.65%. This most likely relates to the experienced manufacturers being the suppliers of wind turbines for all of the large offshore outliers with high cost overruns (ranging from 22 – 44 %) - these are outliers but have an impact on mean cost escalation figures. For the less experienced developers no such outliers occur.

This lends support to the hypothesis that manufacturers with greater historical experience have fewer overruns by frequency.

4. Conclusion and Policy Implications

First, numerous hypotheses examined were not supported by our dataset or corresponding statistical analysis. As Table 5 summarizes, the only two we were able to confirm was H4 about configuration, namely that offshore wind farms see a greater incidence and severity of cost overruns, and H6 about experience, namely that developers with at least five historical projects had a lower median for cost escalation. Surprisingly, perhaps, we were only partially able to confirm our hypothesis about size and diseconomies of scale. There was no significant relationship between the size of a budget and the propensity for an underrun, or between the size of a windfarm in total capacity (MW) and the occurrence of a cost overrun, and only a loose relationship between average turbine size (in MW) per wind farm and the risk of an overrun. Moreover, we could only partially confirm technological learning within a subsample of onshore projects; there was little to no learning within the industry about overruns for offshore wind farms, that is, over time, they did not get less frequent or severe.

Our study points the way towards future areas of both research and industry improvement. The inability to confirm our hypothesis about size and economies of scale, or size of budget and fiscal control, means that small projects and large wind farm projects are almost equally impacted by overruns or likely to exhibit underruns. This rather uniform occurrence independent of project type or size means they are an industry-wide problem affecting small-scale and large-scale manufacturers and developers alike. The industry should begin to compile reliable, rigorous, and transparent data about cost performance so that it can be more rigorously analyzed and better understood. Such efforts would undoubtedly generate a larger sample beyond the 51 windfarms we explored here.

Moreover, the inability to confirm our hypothesis about learning suggests the need for better information sharing and collaborative or joint ventures within the industry. One solution here could perhaps even be the creation of patent pools or a formal institutional platform for sharing best construction practices, to minimize fragmentation and ensure positive experiences are disseminated and negative ones properly documented so that they can be avoided. That Asian and European projects are prone to more severe overruns (also linked to offshore projects) also suggests that regional regulators, or even investors, in those locations start paying more attention to the causes and impacts of overruns. Future research could also normalize underruns and overruns to installed capacity (MW) and begin to assess which particular developers or operators seem to experience the least or most severe construction risks.

Third, and finally, is that while we have documented that almost two-thirds of the windfarms in our sample (61%) suffered from a cost overrun, the mean amount of that overrun (6.5%) was relatively minor compared to other major energy and infrastructure projects, and 20 projects (39%) actually saw construction cost as budgeted or underruns. When compared to nuclear reactors, hydroelectric dams, and a suite of other projects, the data compiled by Table 6 suggests that windfarms are the third least risky (from a cost overruns standpoint) behind solar energy facilities and transmission networks. Thermoelectric power plants, mines, dams, and nuclear reactors all have significantly higher incidences of cost overruns. The ultimate lesson here may be that while to some the inherent construction risks involved with wind energy seem severe in an absolute sense, in comparative terms they have less risk than most. Perhaps this means the construction risk of wind energy should, in actuality, be reframed as a benefit. Construction risk is in a way a positive externality (less likelihood of a severe overrun) that has value and should be monetized as analysts, planners, and investors choose between different energy systems.

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6. Tables

Table 1: Six Hypotheses Related to Construction Risk and Wind Farms

Hypothesis	**Type of analysis**	**Explanation**
H1: Technological learning	Temporal	Fewer cost overruns occur as stakeholders learn from experience over time
H2: Simplicity and fiscal control	Selective (subsample of 19 underruns)	Projects with smaller budgets would exhibit a greater potential for savings through underruns
H3:Economies of scale	Across the entire dataset	As wind turbines and farms get larger in capacity, they become susceptible to a greater frequency and magnitude of cost overruns
H4: Configuration	Comparative	There will be a significant correlation between offshore wind farms and cost overruns
H5: Regulatory regimes and markets	Geographic (based on project location)	Countries with more advanced regulation and improved transparency would exhibit lower and fewer construction overruns than those with weaker regulatory governance
H6: Manufacturing experience	Institutional (based on manufacturer)	Manufacturers and developers with more experience doing projects would have less frequent and less severe overruns

Source: Authors

Table 2: Mean and median cost escalation (%) for wind farms by configuration (n=51) and by foundation for offshore wind farms

Configuration	Number of Projects (N)	Mean cost escalation (%)	Standard Deviation	Median
Onshore	18	0.8	8.4	-0.5
Offshore	33	9.6	13.6	5.7
Foundation Type				
Gravity Based	7	5.4	6.4	-
Monopile	20	7.4	9.4	4.6
Other	4	24.7	8.0	-

Source: Authors

Table 3. Mean and median cost escalation (%) for wind farms by region (n=51)

Region	Number of Projects (N)	Mean cost escalation (%)	Standard Deviation	Median
North America	4	-1.7	8.0	-
Europe	36	7.7	13.27	2.9
Onshore	4	0.36	0.29	-

Offshore	32	9.1	13.6	5.1
Asia	4	9.5	13.5	-
Australia	7	2.7	12.5	-

Source: Authors

Table 4: Mean and median cost escalation (%) for wind farms by manufacturer experience (n=49)

Project experience	Number of Projects (N)	Mean cost escalation (%)	Standard Deviation	Median
Fewer than 5	18	6.99	10.72	4.65
Five or greater	31	6.62	13.96	1.08

Source: Authors. Note: n=49 because two projects were joint ventures involving more than one manufacturer.

Table 5: Summary Results for Hypotheses

Hypothesis	**Result**
H1: Technological learning	Trend towards cost underrun with time for onshore wind farms but not for offshore
H2: Simplicity and fiscal control	No effect
H3: Economies of scale	As wind farms get larger onshore, the cost underrun increases but for offshore the cost overrun increase with size.
H4: Configuration	Onshore wind farms have a mean cost overrun of 0.77% and a median of -0.53% compared to offshore wind farms with a mean overrun of 9.6% and a median of 5.7%
H5: Regulatory regimes and markets	Dominated by the signal from offshore wind farms for Europe. Asian projects are more prone to cost overruns than North American and Australian projects (small samples)
H6: Manufacturing experience	Developers with past experience in at least 5 projects or more see median cost escalation of 1.08% compared to less experienced ones with a median cost escalation of 4.65%

Source: Authors

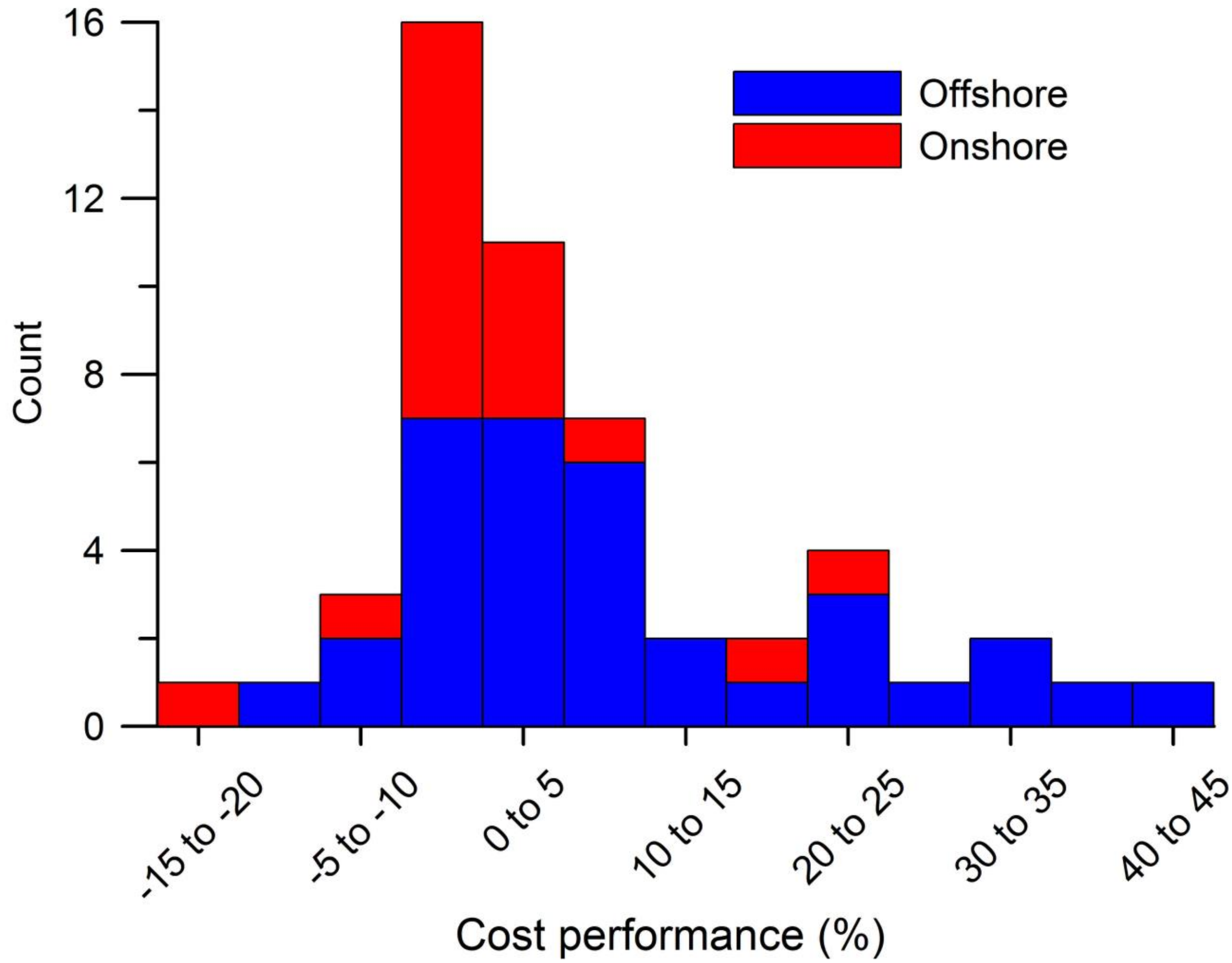
Table 6: Mean Cost Escalation for Various Infrastructure Projects

Technology	Mean Cost Escalation (%)	(n) for the sample
Nuclear reactors	117	180
Hydroelectric dams	71	61
Railway networks	45	58
Bridges and tunnels	34	33
Roads	20	167
Mining Projects	14	63
Thermal Power Plants	13	36
Transmission Projects	8	50
Wind Farms	6.5	51
Solar Farms	1	39

Source: Data for electricity windfarms comes from this study. Data for other items come from Sovacool, BK, D Nugent, and A Gilbert. “Construction Cost Overruns and Electricity Infrastructure: An Unavoidable Risk?” Electricity Journal 27(4) (May, 2014), pp. 112-120.

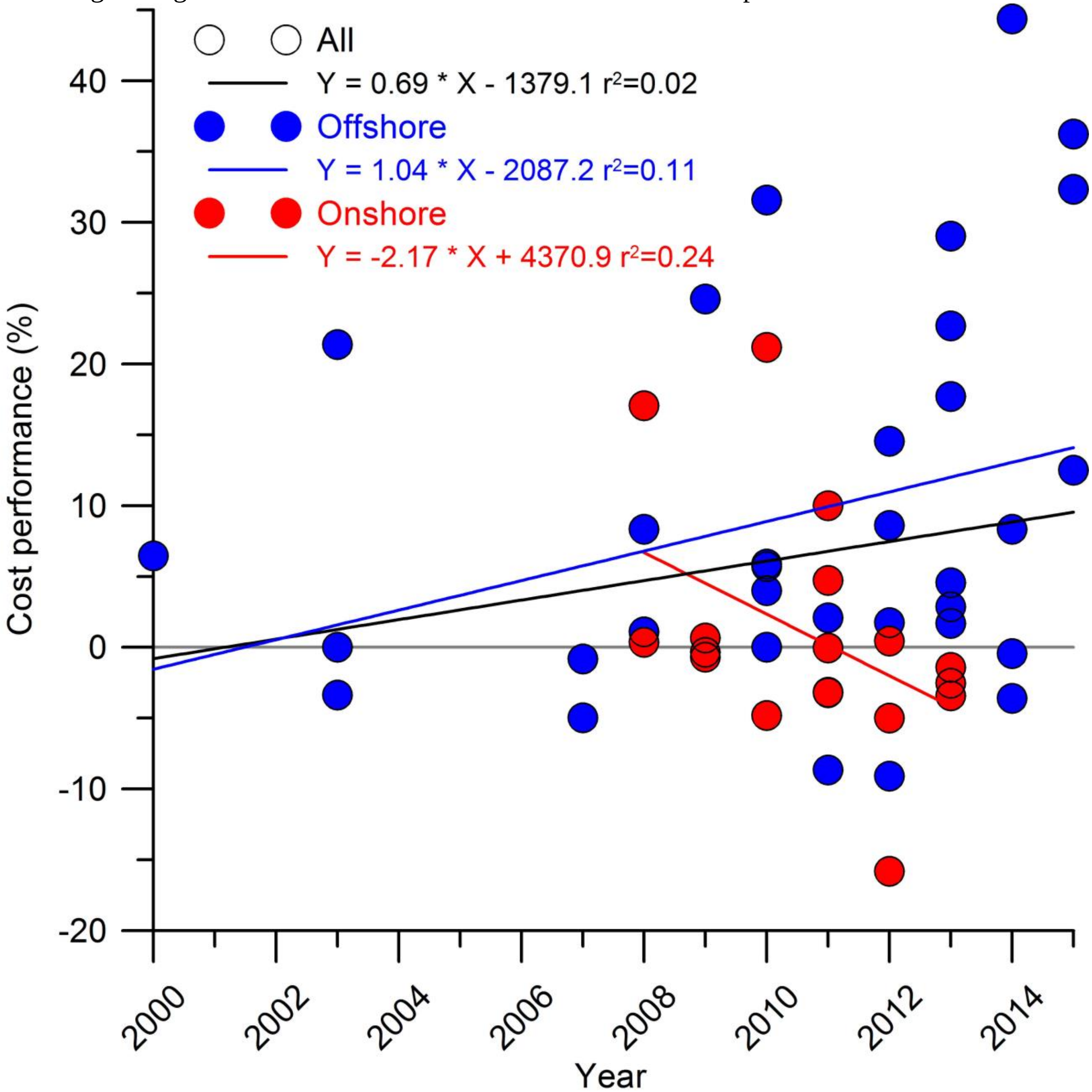
7. Figures

Figure 1: Count of cost performance categories (%) for the 51 wind farms in the database, shown as offshore or onshore by the colored shading.



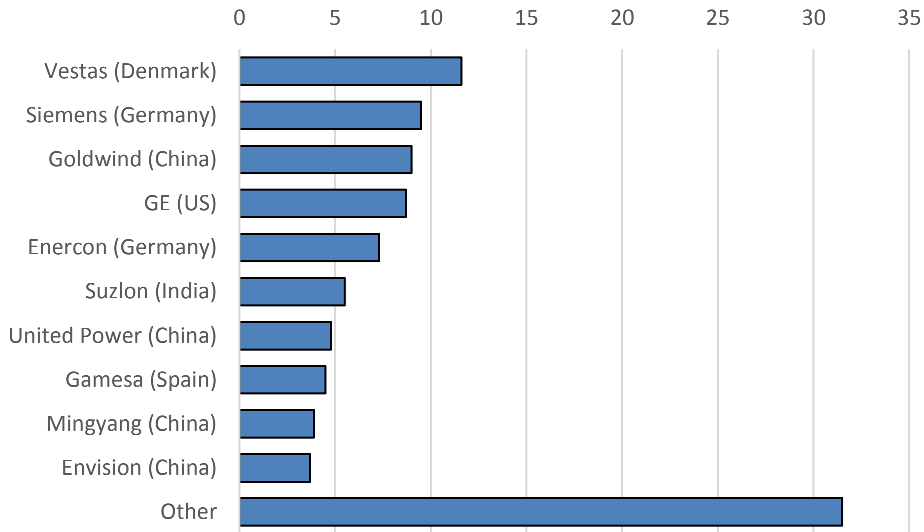
Source: Authors

Figure 2: Cost performance (%) for wind farms by year of commissioning. Linear fits are shown in the legend together with the coefficient of determination from Spearman rank correlation.



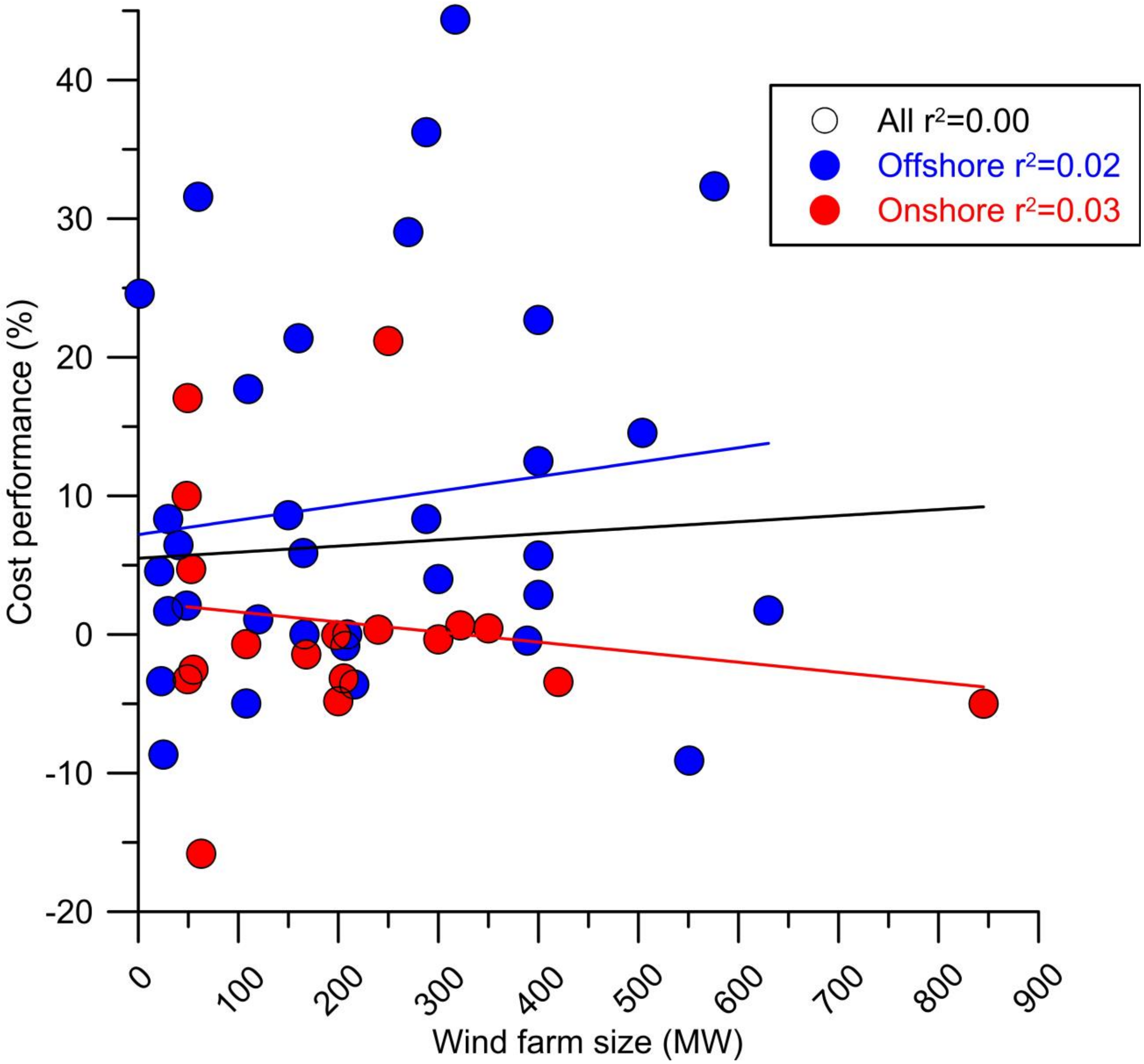
Source: Authors

Figure 3: Leading Wind Turbine Manufacturers by Global Market Share, 2014



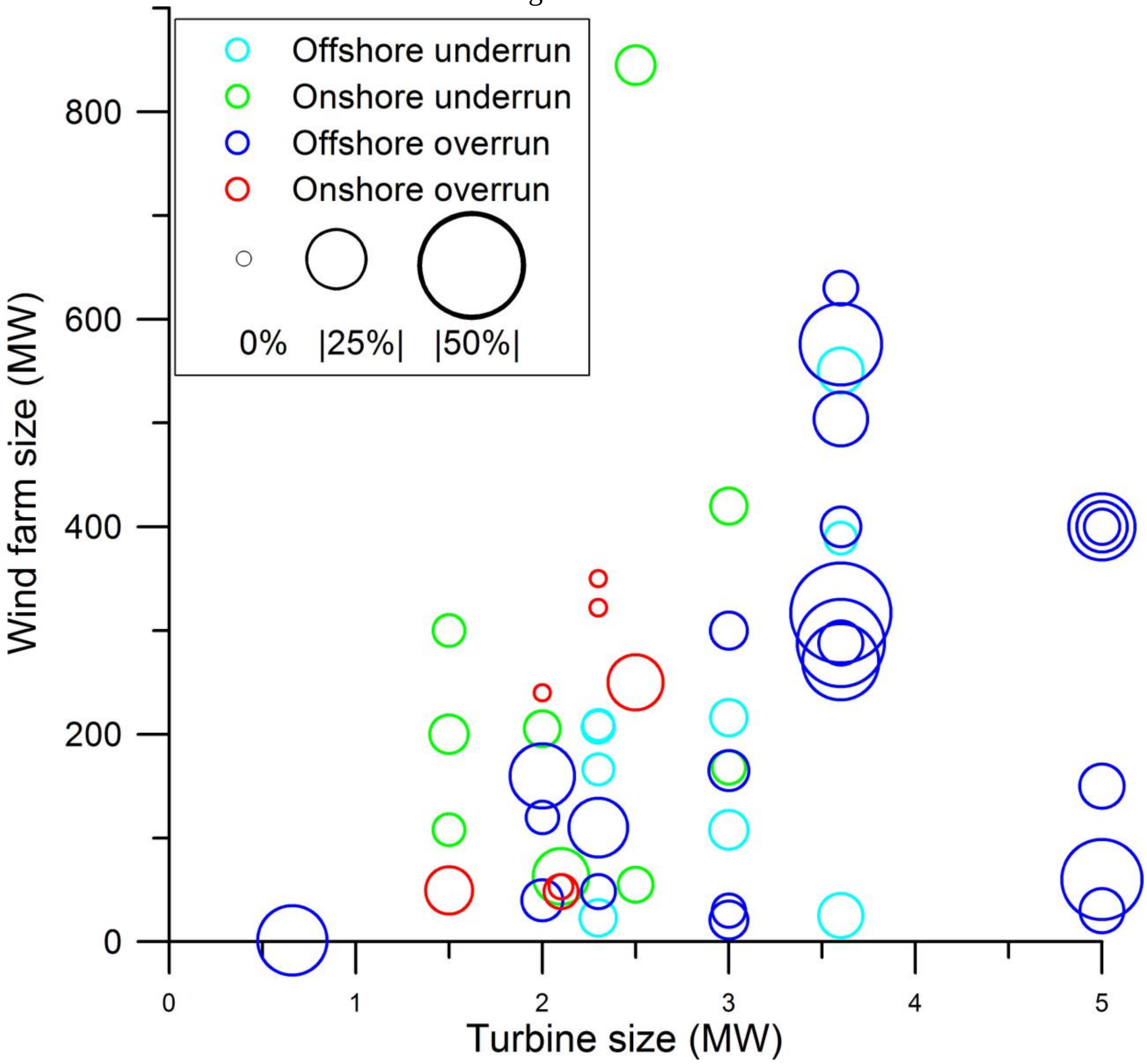
Source: Authors' compilation based on data from the Global Wind Energy Council.

Figure 4. Relationship between cost performance and wind farm size. The coefficient of determination shown in the legend is from Spearman rank correlation.



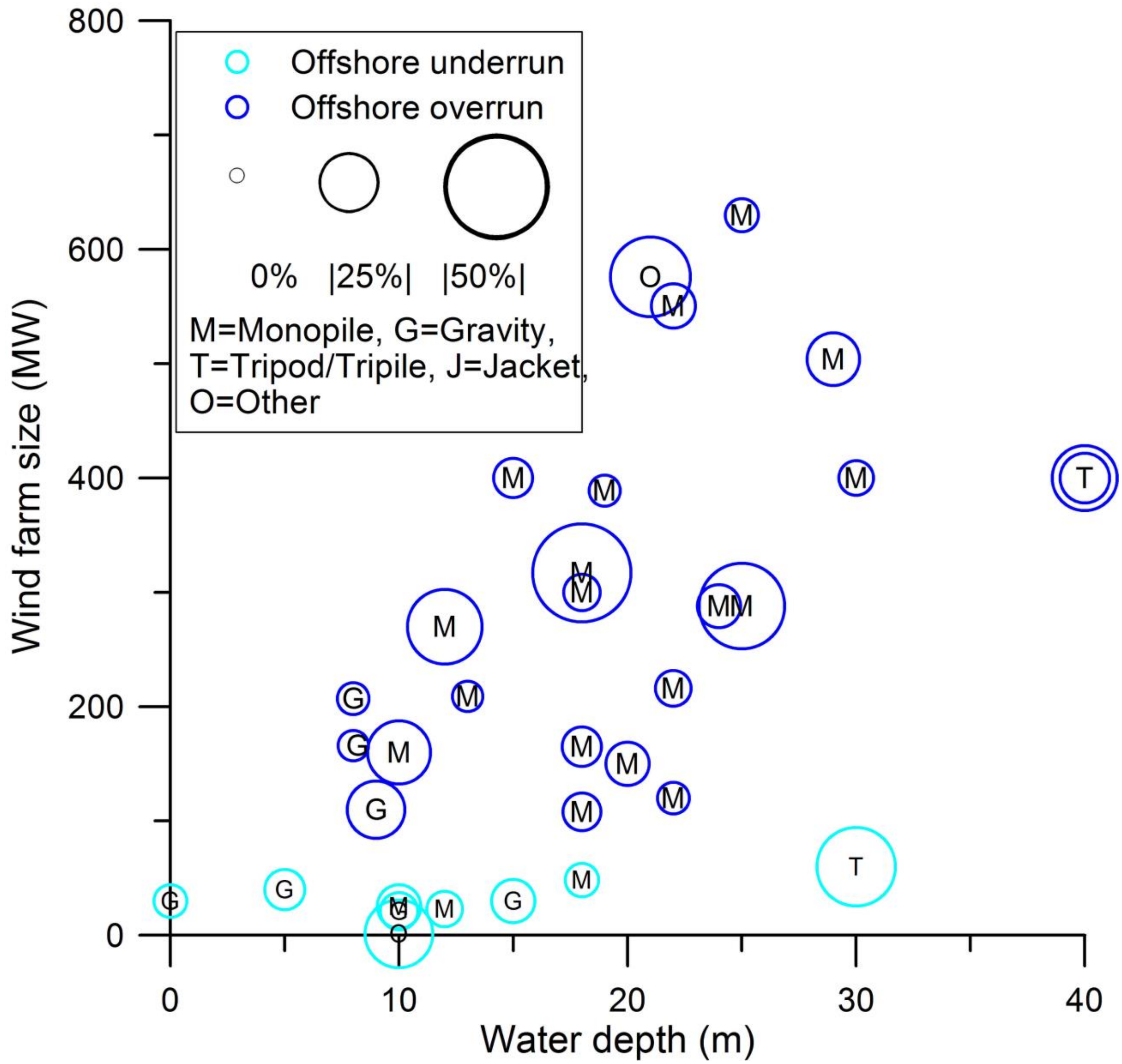
Source: Authors

Figure 5. Bubble plot showing the relationship between cost performance, turbine size and wind farm size for onshore and offshore wind farms. The absolute value of cost underrun/overrun scales with the size of the bubble as shown in the legend.



Source: Authors

Figure 6. Bubble plot showing the relationship between cost performance and water depth for offshore wind farms. The absolute value of cost underrun/overrun scales with the size of the bubble as shown in the legend. The type of foundation is marked by the symbol in the bubble center.



Source: Authors

8. Appendix 1: Construction Cost Overrun Dataset

Date commissioned	Manufacturer	Developer	Configuration	Name	Location	Turbine size	Water depth (m)	Hub-height	Distance to shore (km)	Turbine type	MW	Initial Budget (millions of $2012)	Actual Cost (millions of $2012)	Cost overrun (m$)	Cost overrun (%)
2000	Bonus Energy	Dong	Offshore	Middelgrunden	Denmark	2	5	70	5	Bonus 2.0 MW/76	40	62	66	4	6.45
2003	Bonus Energy	Samsø Havvind	Offshore	Samsø	Denmark	2.3	12	62	4	Bonus 2.3 MW/82	23	44.5	43	-1.5	-3.37
2003	Bonus Energy	Dong	Offshore	Nysted	Denmark	2.3	8	70	11	Bonus 2.3 MW/82	166	363	363	0	0
2003	Vestas	Vattenfall/DONG	Offshore	Horns Rev I	Denmark	2	10	70	18	V80-2MW	160	309	375	66	21.36
2007	Vestas	NordzeeWind	Offshore	Egmond aan Zee	Netherlands	3	18	70	12	V90-3.0 MW	108	261	248	-13	-4.98
2007	Siemens	E.ON	Offshore	Rødsand II	Denmark	2.3	8	70	11	SWT-2.3-93	207	607	602	-5	-0.82
2008	Vestas	Eneco	Offshore	Prinses Amalia Windpark	Netherlands	2	22	60	23	V80-2.0 MW	120	461	466	5	1.08
2008	Senvion/Repower	C-Power/EDF	Offshore	Thornton Bank	Belgium	5	15	95	27	Repower 5M	30	168	182	14	8.33
2008	Enercon	Ventominho	Onshore	Alto Minho	Portugal	2				E-82 2MW	240	508.23	510	1.77	0.35
2008	Goldwind	Goldwind	Onshore	North Longyuan Zhurihe	China	1.5				GW77/1500	49.5	68.34	80	11.66	17.06
2009	Vestas	Setana Town	Offshore	Setana	Japan	0.66	10	47	1	V47-660 kW	1.32	6.1	7.6	1.5	24.59
2009	GE	GE	Onshore	Chateaugay I Wind Park	United States	1.5		77		GE 1.5 MW	108	213.48	212	-1.48	-0.69
2009	Goldwind	Goldwind	Onshore	Bayanzhuoer Wulanyiligeng	China	1.5		85		GW77/1500	300	565	562.96	-2.04	-0.36
2009	Alstom and Siemens	ScottishPower Renewables	Onshore	Whitelee 1	United Kingdom	2.3		65		Siemens 2.3	322	456	459	3	0.66
2010	Siemens	Dong	Offshore	Horns Rev II	Denmark	2.3	13	68	32	SWT-2.3-93	209	635	635	0	0
2010	Vestas	Vattenfall	Offshore	Thanet	United Kingdom	3	18	70	12	V90-3MW	300	1218.02	1266.74	48.72	4
2010	Siemens	Dong	Offshore	Anholt	Denmark	3.6	15	82	15	SWT-3.6-120	400	1685	1781	96	5.7

2010	Vestas	BelWind	Offshore	Belwind 1	Belgium	3	18	72	46	V90 - 3	165	731	774	43	5.88
2010	Senvion/Areva	Deutsche offshore testfeld- und infrastruktur gmbh	Offshore	Alpha Ventus	Germany	5	30	92	56	5m	60	190	250	60	31.58
2010	GE	Dominion Resources	Onshore	Fowler Ridge II	United States	1.5		80		GE 1.5	200	81.11	77.2	-3.91	-4.82
2010	Nordex/GE	BP/Sempra	Onshore	Cedar Creek II	United States	2.5		80		N90/2500	250	392	475	83	21.17
2011	GE	Arklow Energy	Offshore	Arklow Bank 1	Ireland	3.6	10	74	10	GE 3.6 MW Offshore	25.2	60	54.8	-5.2	-8.67
2011	Siemens	Energie Baden-Württemberg (EnBW)	Offshore	Baltic 1	Germany	2.3	18	67	17	SWT-2.3-93	48.3	240	245	5	2.08
2011	Guodain	Guodain	Onshore	Guohua Tongliao Kezuo Zhongqi Phase 1	China			61.5		UP82	49.5	70.26	68	-2.26	-3.22
2011	Vestas	Collgar Wind Farm Pty Ltd	Onshore	Collgar	Australia	2		80		V90-2MW	205.4	774.6	750	-24.6	-3.18
2011	Vestas	Arise Windpower AB	Onshore	Jadraas	Sweden			119		V112 - 3MW	203	446.21	446	-0.21	-0.05
2011	Suzlon (Senvion)	AGL Energy	Onshore	Hallett 5 (The Bluff)	Australia	2.1		80		S88-2.1	53	255	267	12	4.71
2011	Suzlon	Infigen Energy	Onshore	Woodlawn Wind Farm	Australia	2.1		80		S88-2.1	48.3	80	88	8	10
2012	Siemens	Dong	Offshore	Walney 1 &2	United Kingdom	3.6	22	90	14	SWT-3.6-107 + SWT-3.6-120	550.6	1743.17	1584.7	-158.47	-9.09
2012	Siemens	Dong	Offshore	London Array	United Kingdom	3.6	25	87	20	SWT-3.6-120	630	2921.6	2972.2	50.6	1.73
2012	Repower	Vattenfall	Offshore	Ormonde	United Kingdom	5	20	97	10	5M	150	605	657	52	8.6
2012	Siemens	Greater Gabbard Offshore Wind	Offshore	Greater Gabbard	United Kingdom	3.6	29	80	34	SWT-3.6-107	504	1980	2268	288	14.55
2012	Suzlon (Senvion)	AGL Energy	Onshore	Oaklands Hill Wind Farm	Australia	2.1		80		S88-2.1	63	158	133	-25	-15.82
2012	GE	GE	Onshore	Shepherds Flat	United States	2.5		82		GE 2.5	845	2000	1900	-100	-5
2012	Siemens	Scottish and Southern Energy	Onshore	Clyde Wind Farm	United Kingdom	2.3		80		SWP 2.3	350	911	915	4	0.44
2013	WinWind	Innopower	Offshore	Kemi Ajos	Finland	3	0	88	3	WWD-3	30	59	60	1	1.69
2013	AREVA Wind	Trianel	Offshore	Borkum West 2	Germany	5	30	90	44	M5000-116	400	1961	2017	56	2.86
2013	Vestas	Sund & Bælt	Offshore	Sprogø	Denmark	3	10	70	10	V90-3.0 MW	21	66	69	3	4.55
2013	Siemens	Vattenfall	Offshore	Lillgrund	Sweden	2.3	9	68	11	SWT-2.3-93	110	226	266	40	17.7

2013	BARD	Bard	Offshore	Bard Offshore 1	Germany	5	40	90	101	Bard 5.0	400	1807	2217	410	22.69
2013	Siemens	DONG, Siemens, and Centrica	Offshore	Centrica Lincs	United Kingdom	3.6	12	100	8	SWT-3.6	270	1212.33	1564.3	351.97	29.03
2013	Vestas	AGL Energy	Onshore	Macarthur	Australia	3		84		V112 - 3MW	420	1035.5	1000	-35.5	-3.43
2013	GE	Mumbida Wind Farm Holdings Pty Ltd	Onshore	Mumbida	Australia	2.5		84		GE2.5	55	118	115	-3	-2.54
2013	Vestas	Hydro Tasmania	Onshore	Musselroe Bay	Australia	3		80		V90-3MW	168	399.7	394	-5.7	-1.43
2014	Vestas	Northwind	Offshore	Nortwind	Belgium	3	22	72	37	V112 - 3MW	216	1052	1014	-38	-3.61
2014	Siemens	Dong	Offshore	West of Duddon Sands	United Kingdom	3.6	19	90	15	SWP3.6-120	389	2441	2430	-11	-0.45
2014	Siemens	WindMW GMBH	Offshore	Meerwind	Germany	3.6	24	89	23	SWT-3.6-120	288	1200	1300	100	8.33
2014	Siemens	Scira Offshore Energy	Offshore	Sheringham Shoal	United Kingdom	3.6	18	82	23	SWT-3.6-107	317	1186.65	1713	526.35	44.36
2015	Areva Wind	Global Tech 1 Offshore Wind GmBh	Offshore	Global Tech 1	Germany	5	40	90	115	5m	400	1600	1800	200	12.5
2015	Siemens	Gwynt y Môr Offshore Wind Farm	Offshore	Gwynt y Môr	United Kingdom	3.6	21	98	16	SWT-3.6-107	576	2457	3251	794	32.32
2015	Siemens	Vattenfall	Offshore	DanTysk	Germany	3.6	25	88	70	SWT-3.6-120	288	900	1226	326	36.22

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